Leakage of nitrous oxide emissions within the Spanish agro-food system in 1961–2009

Luis Lassaletta · Eduardo Aguilera · Alberto Sanz-Cobena · Guillermo Pardo · Gilles Billen · Josette Garnier · Bruna Grizzetti

Abstract In this paper we examine the trends of nitrous oxide (N_2O) emissions of the Spanish agricultural sector related to national production and consumption in the 1961–2009 period. The comparison between production- and consumption-based emissions at the national level provides a complete overview of the actual impact resulting from the dietary choices of a given country and allows the evaluation of potential emission leakages. On average, 1.5 % of the new reactive nitrogen that enters Spain every year is emitted as N_2O. Production- and consumption-based emissions have both significantly increased in the period studied and nowadays consumption-based emissions are 45 % higher than production-based emissions. A large proportion of the net N_2O emissions associated with imported agricultural goods comes from countries that are not committers for the United Nations Framework Convention on Climate Change Kyoto Protocol Annex I. An increase in feed consumption is the main driver of the changes observed, leading to a remarkable emission leakage in the Spanish

agricultural sector. The complementary approach used here is essential to achieve an effective mitigation of Spanish greenhouse gas emissions.

Keywords Agricultural sector · N_2O emissions · Spain · International trade · Mitigation · Production-based emissions · Consumption-based emissions

1 Introduction

Global emissions of greenhouse gases (GHGs) have steadily increased during the last decade in spite of national and international mitigation efforts (EC 2011). The emissions are unevenly distributed throughout the world, with developed countries having contributed the most (60–80 %) to carbon dioxide (CO_2) emissions and hence to the rise of global temperatures (Wei et al. 2012). Some of these industrialized countries have ratified the United Nations Framework Convention on Climate Change Kyoto Protocol (hereafter Kyoto Protocol) with a GHG reduction commitment (those included in its Annex I) and have effectively reduced emissions, thus accomplishing their initial commitments (Peters et al. 2011). On the other hand, in the same period developing countries (non-annexed in the Kyoto protocol) have increased their emissions, as shown by Peters et al. (2011). Therefore, emissions from the production of internationally traded products have remarkably increased (80 % in the last decade), particularly for commodities produced in developing countries and exported to developed countries (300 % increase).

The reduction of emissions in one country that is obtained by importing products from other countries, increasing the production and the related emissions in the latter, has been labeled emission leakage (Lee et al. 2007). This leakage takes on special relevance when the emissions in an Annex I country of the Kyoto Protocol are replaced by emissions in a non-annexed I country through the trade of commodities (Peters et al. 2011; Barrett et al. 2013). In fact, these international exchanges can be misleading for the global mitigation effort due to internationally fragmented mitigation architecture (Peters et al. 2011). Franks and Hadingham (2012) defined the mitigation achievements that do not produce a real net global reduction of emissions as trivial solutions.

To fully address an effective change in GHG emissions, several authors recommend the study of consumption-based emissions in addition to the conventional analysis of production-based emissions (Peters and Hertwich 2008a; Wiedmann 2009; Barrett et al. 2013). Production-based emissions, as reported by the national inventories, are the emissions produced in a national territory from its production. Consumption-based emissions are the emissions related to the production of the commodities consumed in a particular country and thus include the foreign emissions associated with the production of imported products and exclude domestic emissions associated with exported products. In recent years, several studies have been published using the concept of consumption-based emissions (e.g., Peters and Hertwich 2008a; Wiedmann 2009; Peters et al. 2011; Cadarso et al. 2012). Barrett et al. (2013) consider that despite the general agreement on the importance of this alternative approach, it has not yet been translated into a clear policy.

The increase of global emissions of nitrous oxide (N_2O) is one of the consequences of the deep perturbation of the global biogeochemical nitrogen (N) cycle that has occurred during the last century, principally driven by the production of food and feed (Bouwman et al. 2013). Lassaletta et al. (2014a) have shown how international trade of food and feed has become an important factor shaping the global N cycle. In fact, international trade permits the disconnection between crops and livestock farming (Naylor et al. 2005; Billen et al. 2010), decreasing N use efficiency (NUE) at the global scale (Billen et al. 2013). Also, other factors are affecting the current configuration and inefficiency of the global N cycle, such as the increase in the consumption of animal-based products and the rise in food waste (Steinfeld and Wassenaar

2007; Grizzetti et al. 2013; Sutton et al. 2013). Additionally, international trade leads to the outsourcing of negative impacts of environmental reactive N emission by the agricultural production sector (Galloway et al. 2007; Leach et al. 2012). In the specific case of N_2O emissions, the effect of trade might produce N_2O leakage.

The role of some countries as net importers or exporters of goods and services is not necessarily the same for general commodities as for agricultural products. For example, France and the United States (US) are net importers of emissions embodied in goods and services, whereas China is a net exporter (Davis et al. 2011; Jakob and Marschinski 2013). However, when examining the agro-food system, the situation can be completely different. In 2009, the United States and France were net exporters of protein embedded in food and feed commodities, while China was a net importer (Lassaletta et al. 2014a). For this reason the agricultural sector deserves particular attention in studies focused on comparing consumption and production emissions. Moreover, the international trade of agricultural products can have unexpected consequences of environmental and economic significance. For example, Paulot and Jacob (2013) have recently shown how the environmental consequences of US agricultural export could offset the economic benefits of this activity. Unfortunately, despite this reality these studies are still too few and far between (e.g., Audsley et al. 2009).

Spain's agro-food system has evolved from a relatively balanced situation between protein export and import in 1961–1965 to substantial dependence on external imports in 2005–2009 (Lassaletta et al. 2014b). During the last 50 years, the Spanish agricultural sector has been highly intensified and the inputs of new reactive N have increased threefold. The main driver of the changes observed is an increase in livestock production mainly related to a rise in the proportion of animal protein in the diet of the Spanish population (Lassaletta et al. 2014b). Due to the particular characteristics of the Mediterranean catchments, with irrigation and many reservoirs increasing water residence time, the largest share of reactive N applied in agriculture is locally stored (namely in aquifers) or emitted in gaseous form, instead of being exported to the sea (Lassaletta et al. 2012; Romero et al. 2013). The consequences of the excess N circulating in Spain have been addressed in relation to different reactive N forms such as nitrate (Lassaletta et al. 2009, 2010; Monteagudo et al. 2012), ammonia and N_2O (Sanz-Cobeña et al. 2008, 2012), and nitrogen oxides (Maté et al. 2010), which are leading to atmospheric deposition of N compounds (Avila et al. 2010) and/or biodiversity impairment (Ariño et al. 2011).

In this paper, we present for the first time a long-term evaluation of the N_2O emissions associated with the Spanish agro-food system, including the agricultural sector and the international trade of agricultural goods to and from Spain. The specific aims are: i) to estimate the N_2O emissions associated with the production of the Spanish agricultural sector in comparison to those related to the consumption of the Spanish population during the last five decades (1961–2009); ii) to study the relative contributions of different commodities (primary crops, processed and livestock products) to the N_2O emissions and their trends and iii) to evaluate the relationship between Spain and the other countries of the world in terms of export/import of N_2O emissions and the associated emission leakage. The results obtained in this study are valuable not only for policy makers and society in the search for true mitigation (intended as non-trivial solutions), but also for understanding the structure of the national agro-food system and its recent changes.

2 Methods

This work is mainly based on the data provided for Spain by the food balance sheets module of the FAOSTAT (2013) database, covering the 1961–2009 period. The module contains information on the weight of commodities produced, consumed, exported and imported yearly by Spain. We applied N_2O emission factors (EFs) gathered for all commodities. These specific EFs were obtained from different sources (Appendix) and they are expressed as g N-N_2O/kg of product. The commodities can be classified into: 1) primary crops, 2) processed vegetal products and 3) animal products. We assessed the N_2O emissions associated with the agricultural production within the Spanish territory (production-based emissions) and those related to the food/feed consumption of the Spanish population (consumption-based emissions). The approach to estimate N_2O emissions associated with production differs from that used in the national inventories because in this study the emissions are calculated by kilogram of product instead of by surface of cropland. We used EFs valid at the farm gate, thus taking into account crop and livestock management. Nitrous oxide emissions from fertilizer production are also considered.

In this work we used static EFs for the entire period. The availability of EFs in the literature is rare and the estimate of particular EFs for previous conditions is a huge task beyond the aims of this paper. EFs in crops are affected by a combination of several variables such as fertilizer type and amount, soil and climatic conditions, and yield. NUE is a variable that integrates all this information. The NUE of the Spanish agricultural system has remained relatively constant during the period studied according to Lassaletta et al. (2014b): 50 % in 1961–1965 and 44 % in 2005–2009. As a result, the EFs in the initial period of the study could be similar or slightly lower than that of the final period.

Regarding animal items, a gradual increase in livestock productivity and yields might be expected along the studied period, due to the introduction of more specialized management practices and genetic selection. For manures, overall changes in farm management from solid storage to liquid manure systems are likely to have occurred, particularly in cattle and dairy production (*Bos primigenius*). As a consequence, EFs may generally have decreased in the last few decades compared to those in the 1960s and 1970s (Capper et al. 2009; Gerber et al. 2010). Nevertheless, since production systems have been intensified, several issues may have appeared with a contrasting influence on the EFs. This issue has recently been shown by Soussana and Lemaire (2014) regarding nutrient imbalances in grazing intensification gradients. The increase of the protein content in modern diets, together with the high concentration of farms in specific areas and their disconnection with croplands, have contributed to problems optimally managing animal manure (i.e., excreted N), thus leading to undesirable losses of reactive N forms (del Prado et al. 2013). Moreover, significant reductions in animal fertility and longevity, and a higher incidence of health problems have also been noted as a consequence of selection for increasing production (Oltenacu and Broom 2010). Thus, animal EFs may have been reduced during the last few decades due to changes in some drivers. However, these reductions could be offset by changes in other drivers operating in the opposite direction. Finally, changes in the emissions related to an increase of liquid manure production (pig slurries) associated with the significant growth of pig (*Sus scrofa domestica*) production are taken into account in our approach due to the application of specific EFs for each livestock type.

Production and consumption emissions must be estimated differently for the three types of products, as explained below, paying attention to avoiding double counting (Table 1). Some products that are only used for feeding animals, such as cakes or fodder crops, are not present in the FAO food balance sheets and their emissions have been estimated by taking information on exports, imports and production provided in the trade and production modules of the FAOSTAT database. In this paper, N_2O emissions are expressed as N-N_2O, that is N_2O*0.64.

Table 1 Origin and type of emission factor used for the commodities studied

Type	Category	N° Items	Origin of the data (FAOSTAT)	EF national production[1]	EF import/ export
Primary crops	Cereals	9	Food balance sheets	x	x
Primary crops	Fruits	11	Food balance sheets	x	x
Primary crops	Oilcrops	10	Food balance sheets	x	x
Primary crops	Pulses	3	Food balance sheets	x	x
Primary crops	Spices	4	Food balance sheets	x	x
Primary crops	Starchy Roots	4	Food balance sheets	x	x
Primary crops	Stimulants	3	Food balance sheets	x	x
Primary crops	Sugarcrops	2	Food balance sheets	x	x
Primary crops	Treenuts	1	Food balance sheets	x	x
Primary crops	Vegetables	3	Food balance sheets	x	x
Primary crops	Fodder crops	13	Production + Trade	x	x
Processed vegetal products	Beverages	5	Food balance sheets	not needed	x
Processed vegetal products	Sugar & Sweeteners	4	Food balance sheets	not needed	x
Processed vegetal products	Vegetable Oils	13	Food balance sheets	not needed	x
Processed vegetal products	Cakes	11	Production + Trade	not needed	x
Animal products	Meat	5	Food balance sheets	x	x[2]
Animal products	Other	4	Food balance sheets	x	x[2]

[1] More information about emission factors source (EFs) is presented in the Appendix

[2] EFs for national animal production differ from those for imports and exports. See Material and methods for details

2.1 Primary crops

The FAO food balance sheets provide information on 50 primary crops including cereals, starchy roots, sugar crops, pulses (*Phaseolus* sp., *Pisum* sp., *Vicia faba*, *Cicer arietinum*, *Lens culinaris*), tree nuts, oil crops, vegetables, fruits, stimulants and spices (Table 1; Appendix). We have applied the same N_2O EF, assumed to be representative of the world average, for locally produced and imported products. In order to obtain as robust data as possible, the EFs were based on the average of available worldwide data obtained in the published literature and in life cycle assessment (LCA) databases (USDA 1998; Nielsen et al. 2003; Ecoinvent Centre 2007; Hergoualc'h et al. 2007; Audsley et al. 2009; Nemecek et al. 2011).

For grapes (*Vitis vinifera*) and olives (*Olea europaea*), since no published data were available, a specific Spanish factor was estimated using fertilizer recommendations from MAGRAMA (2012a) and yield and surface data from FAOSTAT. We re-calculated the N applied to each crop by equalling total N inputs to Spanish cropland with those reported by Lassaletta et al. (2014b). IPCC (2006) emission factors were then applied to calculate N_2O emissions. For fodder crops, which are not included in the FAO food balance sheets, we estimated the yearly emissions associated with production using the data from the FAOSTAT production module, which provides information on 13 fodder crops. The export and import of the fodder crops were calculated by means of the data provided in the FAOSTAT trade module.

The emissions associated with Spanish consumption were calculated as proposed by Peters and Hertwich (2008a): Consumption = Production + Imports−Exports. We do not aim at providing an alternative figure of total emissions to that estimated by the national inventories, but we sought to compare production with consumption emissions. However, to evaluate the coherence of our approach, we compared the total emissions resulting from the production of some products with the values provided by the national inventories. For each commodity, the proportion used as feed was calculated by dividing the amount available for consumption (domestic supply quantity) by the amount used for feed. Both figures are provided in the FAO food balance sheets for every year.

2.2 Processed vegetal products

The emissions related to the cultivation of the primary crops in Spain needed for the production of processed products, such as wine and olive oil, have already been estimated in the previous primary crop calculations (e.g., grapes and olives). To estimate the emissions associated with their consumption, we have added the information on imports and exports of these commodities. The FAO food balance sheet provides yearly data of 22 processed products including sugar and sweeteners, vegetable oils and beverages (Table 1; Appendix). We calculated the amount of raw materials needed for the production of every processed commodity and we distributed N_2O emissions between the co-products using economic allocation (Appendix). The products used only for feed such as cakes are not present in the FAO food balance sheets. As we did for fodder crops, we used the information on imports and exports provided in the FAOSTAT trade module.

2.3 Animal production

The calculation of N_2O emissions associated with animal products requires particular attention. We considered different EFs for production, imports and exports, in order to reflect differences between Spanish and foreign production systems, and to avoid double counting of emissions involved in other sections of the study. We used the data on production of the FAO food balance sheets and we only considered N_2O emissions associated with manure management and direct excretion of grazing animals to pasturelands. Emissions associated with animal production but taking place in croplands (i.e., those resulting from manure application, grazing animals in croplands and feed production) were not accounted for here because they are already included in the crop production section. At this stage, we used the specific EFs estimated for Spain by Leip et al. (2010) (Table 1; Appendix). Their EFs for Spain are coherent with those obtained in particular studies for certain Spanish regions (Iribarren et al. 2011; del Prado et al. 2013; Ripoll-Bosch et al. 2013). To estimate the proportion of excretion on pasturelands in relation to that applied to crops, we used the information provided in the BNAE (2011).

To account for imported N_2O emissions related to animal products, we used general EFs for the imported commodities of the FAO food balance sheets. These general EFs were based on a weighted mean from several sources considering the different origin and imported quantities of every item. These EFs also take into account the emissions from feed production (Schenck 2006; Cederberg et al. 2009; Vergé et al. 2009; Leip et al. 2010; da Silva et al. 2010). The same approach was followed for exports but applying the complete EFs (i.e., including feed production) specific for Spain (Leip et al. 2010).

All these calculations require a last correction for meat because production data include not only national production (indigenous meat), but also those animals imported alive that are slaughtered in Spain. To make this correction, we took the information on imports of live animals provided in the FAOSTAT Trade module, estimated the weight per head according to the yield and finally calculated the total weight of meat from imported animals. We calculated the associated emissions using the general and complete factors (including crop and livestock management, although not specific to Spain), and this amount was subtracted from the production figure and added to the import account. Finally, the animals that were bred in Spain but exported as live animals were taken into account. In this case only the part related to feed production was considered, since the other emissions were accounted for before and must be considered as exported (See Appendix for an example).

2.4 Outsourcing of N_2O emissions

The FAOSTAT Trade module provides the origin and fate of the main products that Spain imports and exports to and from the rest of the world countries in 2009. This module includes detailed information on the export and import of 572 commodities. We considered the commodities that together represent two-thirds of the total import and export (12 and 28 commodities, respectively). We assigned an EF to each product and we calculated, for every country, the N_2O emissions outside Spain associated with the production of commodities imported to Spain and the emissions within the Spanish territory that are finally exported abroad. We then obtained a net emission value associated with the trade of agricultural commodities in a country by subtracting the emissions related to exports to Spain from those related to imports from Spain:

$$\text{Net emission} = \sum\nolimits_{1-12}(\text{import commodities} * \text{EF}) - \sum\nolimits_{1-28}(\text{export commodities} * \text{EF})$$

Following the terminology introduced by Peters et al. (2011), when this value is positive it means that this country is net emitting for Spain (we consider that this country is net exporter of N_2O emission to Spain); in contrast, a negative value means that the country is net consuming Spanish N_2O emissions (we consider that this country is a net importer of Spanish N_2O emissions). These calculations have been defined as the balance of emissions embodied in trade by Muradian et al. (2002). In this approach we have not taken into account the re-exports. However, in a recent paper, Lassaletta et al. (2014a) studied the proportion of re-exports compared to direct exports (for proteins). They concluded that the re-exports can be considered negligible, with some exceptions such as the Netherlands, and even in this case they are only significant for a small number of products. Even though any outsourcing of the emissions associated with products nationally consumed can be considered as emission leakage, herein we have considered that N_2O emission leakage occurs when a country that is net emitting for Spain does not belong to Annex I of the Kyoto Protocol.

3 Results

3.1 Production-based emissions

The N_2O emissions associated with agricultural activities in Spain have doubled during the last five decades, from 12.8 Gg of N-N_2O in 1961–1965 to 25.8 Gg of N-N_2O in 2005–2009. Nitrous oxide emissions in Spain have evolved in parallel with the increasing Net Anthropogenic N Input (NANI = synthetic fertilizers + net atmospheric deposition + crop biological fixation + net import of food and feed) entering Spain yearly, which is associated with the intensification of agricultural activities (Fig. 1). Approximately 1.5 % of the NANI entering Spain every year is being emitted as N_2O as a result of agricultural production.

Nowadays the N_2O emissions associated with primary crop production account for 67 % of the total. Direct animal emissions account for 33 %, while at the beginning of the 1960s they were 21 % (versus 79 % for primary crop production). However, the EFs for animal production in Spain are calculated considering manure management and animal grazing only. Indeed, emissions from the fertilization of crops with manure as well as those from feed production are considered in the emissions of primary crops. Therefore, the real contribution of animal production will be higher when considering all the stages of the animal production.

Table 2 shows the contribution to N_2O emissions in 1961–1965 and 2005–2009 of the five crops that produced together about 70 % of the total emissions associated with primary crop production for 1961–1965 and 2005–2009. Wheat (*Triticum* sp.), barley (*Hordeum* sp.) and maize (*Zea mays*) are on the list of the most emitting crops in Spain for both periods and potatoes (*Solanum tuberosum*) belong to the first period's list and they have now been substituted by olives and vegetables (Table 2). The proportion of wheat used as feed has changed over time (Table 2). In the 1960s all the wheat was for human consumption, while now 57 % is used for feed. The proportion of barley and maize used for feed has remained constant and high, but their absolute consumption has significantly increased. Thus, in the 1960s only 30 % of the emissions of major commodities were associated with feed production and now this share has increased to 60 %. We can therefore conclude that a large part of the increase in N_2O emissions is associated with feed production.

The emissions associated with animal production (manure management and direct excretion to pasturelands) have increased threefold in the last five decades from 2.7 Gg of N-N_2O in 1961–1965 to 8.4 Gg of N-N_2O in 2005–2009. N_2O emissions from bovine meat production account for the largest share in both periods (52 % and 43 %, respectively). The most remarkable change was observed in the increase of the emissions related to pig meat production, which accounted for 9 % in the first period and 33 % in the second one.

We observed full coherence between the approach of this work, based on the amount of products, and the results reported by the national inventories, which are based on emissions by surface (MAGRAMA 2012b). According to the national inventories, the N_2O emissions associated with the Spanish agricultural sector in 2009 were 29.1 Gg of N-N_2O, whereas we estimated this at 26.1 Gg of N-N_2O for the same year.

Fig. 1 Relationship between Net Anthropogenic Nitrogen Input (NANI; data from Lassaletta et al. 2014b) and N_2O emissions in Spain during the 1961–2009 period

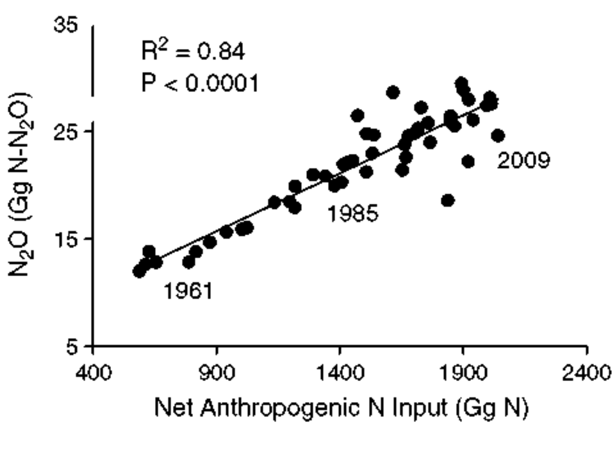


Table 2 Emissions of the five commodities that have contributed the most to the N_2O emissions of Spanish agriculture in 1961–1965 and 2005–2009 (average annual emissions). The proportion of the crops used as feed is also provided

1961–1965			2005–2009		
Commodity	N_2O Emission (Gg N-N_2O)	% used as feed	Commodity	N_2O Emission (Gg N-N_2O)	% used as feed
Wheat	2.7	0	Barley	4.3	83
Barley	1.0	83	Wheat	3.3	57
Pulses, Other	0.5	56	Maize	1.2	83
Potatoes	0.5	3	Olives	1.1	0
Maize	0.4	88	Vegetables, Other	0.6	5

3.2 N_2O emissions related to production vs. consumption

N_2O emissions associated with Spanish imports (i.e., commodities produced in other countries and exported to Spain) and exports (i.e., produced in Spain for the production of commodities and then exported abroad), both significantly increased during the period studied (Fig. 2a). However, the emissions associated with import have always been higher than those related to export and this difference has grown progressively. As a result, the net emissions already positive in the 1960s increased sevenfold in the period studied, from 1.9 Gg N-N2O in 1961–1965 to 11.6 in 2005–2009.

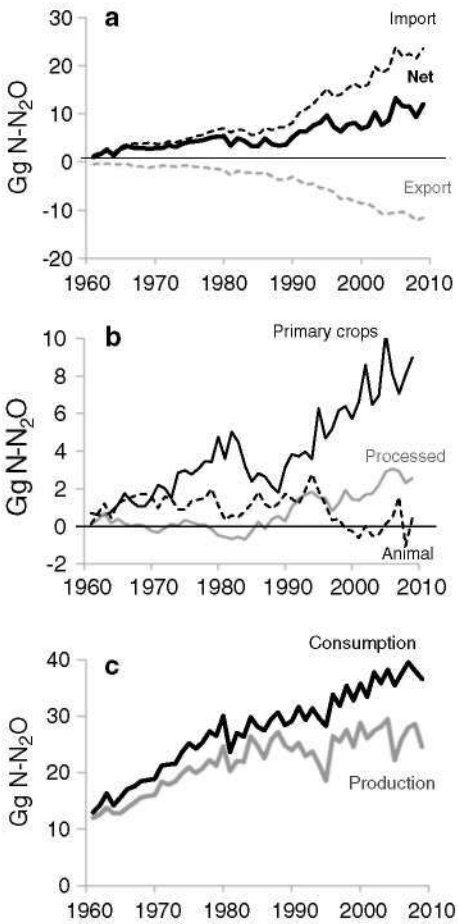
Primary crops are the category of products that most contributed to the observed high values of net import of N_2O emissions embedded in imported commodities (Fig. 2b). This is due to a very high import of cereals and soybeans (*Glycine max*) that is not compensated by the export of citrus (*Citrus* sp.) or vegetables. For example, in Spain in 2009 the N_2O emissions related to the import of wheat, soybeans and maize were 4.4, 2.5 and 1.5 Gg N-N_2O, respectively. In contrast, the emissions related to the export of citrus and vegetables totaled 1.2 Gg N-N_2O. For processed crops we found a similar situation: in 2009 the emissions associated with soybean cakes imported to Spain (1.7 Gg N-N_2O) alone were higher than the emissions associated with the export of olive oil and wine (1.2 Gg N-N_2O) (Fig. 2b). For animal products the situation is different: during the first 35 years the balance of emissions was positive and the import of milk and bovine meat contributed the most. However, in the last 15 years the balance was close to zero due to a significant increase in the export of pig meat (Fig. 2b).

To calculate the consumption-based emissions for Spain, we added these estimated net values to the production-based emissions. We observed that the consumption-based emissions rose progressively and faster than the production-based emissions (Fig. 2c), so that this difference increased during the period studied (14.6 % and 44.9 % higher in the first and the last period, respectively).

3.3 Net emissions throughout the world

Figure 3 shows the behavior of the world countries as net importers or net exporters of N_2O emissions associated with the most imported and exported agricultural commodities to and from Spain in 2009. The nature of the most imported products differs greatly from that of the

Fig. 2 **a** Evolution of N_2O emissions associated with the export and import of food and feed to Spain; **b** evolution of net N_2O emissions from the export and import of primary crops, processed crops and animal products; **c** comparison of production- and consumption based N_2O emissions from the agricultural sector



exported commodities. There is a clear specialization in the export of high-economic-value products such as citrus, wine, vegetables, olive oil and pig meat, while the import is dominated by low-value products (wheat, maize, soybean cakes and barley). Similarly, a relatively specialized relationship between Spain and the other countries can be observed. Brazil and Argentina are the countries with the highest net N_2O emissions exported to Spain (2.4 and 1.3 Gg of N-N_2O, respectively) linked to the production of soybeans in the case of Brazil and soybean cake production in Argentina. Italy and Portugal are the countries that most net imported N_2O emissions in 2009, related to the import of pig meat and olive oil. The behavior of the European non-Mediterranean countries is not uniform, being either net exporters or net importers of N_2O emissions to Spain. For example, France, as a net N_2O exporter, imports a significant amount of products causing emissions in Spain, mainly coming from the production of pig meat, citrus and olive oil, but not enough to offset the N_2O emitted in the production of wheat and barley that France exported to Spain. The case of Germany is the opposite because, even though the emissions associated with the export of grain to Spain are significant, those associated with the import of pig meat, citrus and wine are larger.

We can conclude that a sizable phenomenon of N_2O emission leakage currently occurs in Spain. In 2009, 72 % of the net N_2O emission imports from the most traded commodities came

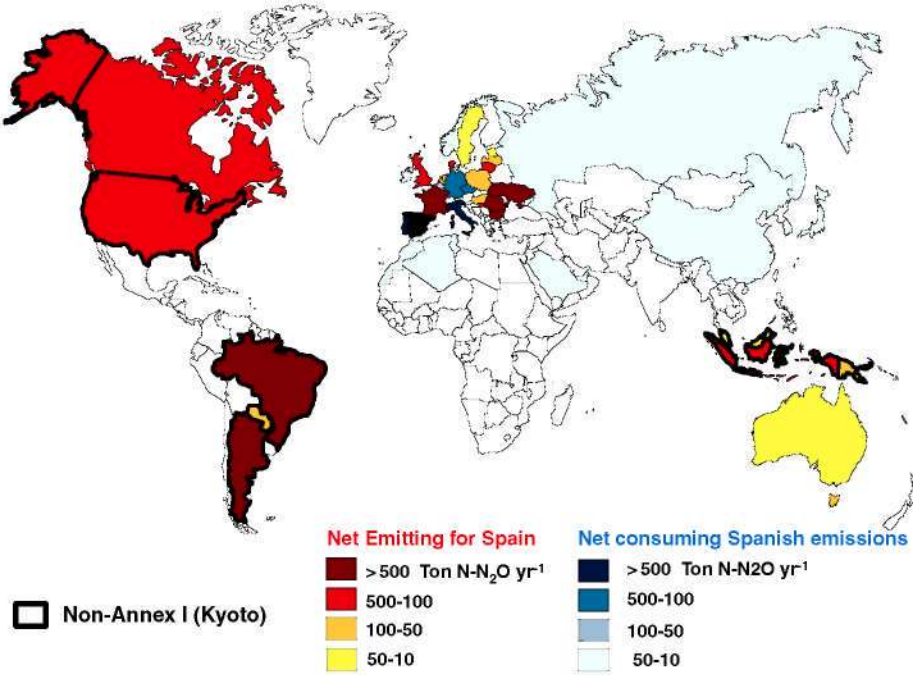


Fig. 3 Map of the countries that most net import (*blue*) or net export (*red*) N_2O emissions embodied in agricultural commodities to and from Spain (*Black*). Countries not belonging to Annex I of the Kyoto Protocol have been highlighted

from countries not included in Annex I of the Kyoto Protocol, that is, without a GHGs reduction commitment. The net imports from Brazil, Argentina as well as from the US, Indonesia and Paraguay are the main contributions to this N_2O leakage in Spain.

4 Discussion

The results of this study show a progressive increase in the gap between production- and consumption-based N_2O emissions in Spain during the last 50 years. The high proportion of net imported emissions from non-Annex I countries has led to emission leakages, which may be even higher in the short term since some countries acting now as net emission exporters to Spain (e.g., Canada) have not ratified the new agreement of the Kyoto Protocol at 2013.

Contrary to what has been assessed for overall Spanish economic activity, in the agricultural sector consumption-based N_2O emissions have always been higher than production-based N_2O emissions throughout the period studied. This could not be evident because of the well-known intense trade of vegetables and pig meat from Spain to northern Europe. According to Sánchez-Chóliz and Duarte (2004), the Spanish economy had a slightly exporting behavior in 1995. This situation changed thereafter, increasing the net importation by Spain of CO_2-equivalent emissions embodied in goods and services during the last decade (Arto et al. 2012; Cadarso et al. 2012). Regarding the agricultural sector, the present results show that the amount of consumption-based emissions has always been high (32 % on average in the 1995–2009 period). The role of Spain in the European agro-food sector is reflected in the differences between the patterns of N_2O emissions and those of other environmental indicators, such as the water footprint. Spain is the largest exporter of virtual water to several European countries, even to countries from which it is a net importer of N_2O emissions (e.g., France) (Steen-Olsen et al. 2012). The main reason behind this is the export of highly irrigated crop products such as vegetables.

In contrast, the significant increase of consumption-based emissions in Spain is related to the conversion of vegetal to animal protein, since the majority of the N_2O emission imports correspond to feed production. In the last 15 years, the production of pig meat for export has remarkably increased. However, these related emissions are compensated by those associated with the beef and cow's milk imported by the country. We conclude that the imbalance observed is driven by the increase in animal protein ingestion by Spaniards in the last 50 years, both in terms of total protein ingestion per capita and in the share of animal protein in the diet (Lassaletta et al. 2014b). On the other hand, Grizzetti et al. (2013) have shown how in European countries the food waste rate at the consumption level is among the highest of the world, concluding that a proportion of the N_2O emitted arises from the production of food that will in the end be wasted by consumers. Indeed, Spain has sixth highest level of food wastage of any European Union (EU) country (MAGRAMA 2013). Consequently, we consider that the N_2O emission leakage occurring in Spain is not the result of a particular climate policy but is being triggered by market and consumption patterns. This type of emission leakage has been defined as weak leakage by Peters and Hertwich (2008b).

Despite the Spanish emission leakage observed in all economic sectors, most particularly in the agricultural sector, and even with the decrease in total GHG emissions of the last 5 years, probably due to the economic crisis, in 2012 Spain was still above the emissions ceiling it had committed to in the Kyoto Protocol (WWF 2013). Effective mitigation and also adaptation strategies can be of special importance in Spain due to the expected significant vulnerability of this country to climate change (Iglesias et al. 2011; Trnka et al. 2011; Iglesias et al. 2012). In addition to its direct vulnerability to the consequences of climate change, Spain is currently net importing the same amount of protein as is produced by its agricultural sector (Lassaletta et al. 2014b). This external dependence, together with the high dependence on fossil fuel-based inputs, implies a high level of vulnerability of the Spanish agro-food system to market fluctuations.

Several authors have undertaken the analysis of policy options to avoid emission leakage. Firstly, it is very important to recognize the significance of the complementary information provided by the consumption-based approaches, which make it possible to properly understand the actual contributions of different sectors and countries to GHG emissions (Barrett et al. 2013). Although a huge challenge, it is generally recognized that unilateral national policy measures not synchronized with foreign policies generate a fragmented mitigation architecture leading to ineffective mitigation and resulting in an increase of emission leakages (Lee et al. 2007; Peters et al. 2011). Antimiani et al. (2013) argued that global cooperative solutions would be the most effective strategy to reduce emission leakages. Cadarso et al. (2012) compiled several alternative options for Spain including the co-responsibilities of producers and consumers, the establishment of trade taxes and the adoption of the EU the Climate and Energy Package guidelines, which include the effects of industry de-localization.

Mitigation strategies that substitute traditional food production with forest or biofuel, maintaining consumption unchanged by importing food from other countries, will only increase emissions in those countries, thus producing emission leakages. Therefore, for true mitigation, strategies targeting national agricultural production will be much more effective (Lee et al. 2007). This is the case for Spain and particularly if no changes in consumption occur. We advocate acting simultaneously in both directions, on agricultural mitigation as well as consumption (including reduction in food waste). Regarding the mitigation measures in the agricultural sector, we consider particularly valuable those measures including on-site improvements in soil organic matter and irrigation water management, not only for their positive effects on emission mitigation but also for the added value as adaptation strategies, through, e.g., water savings and erosion control (Aguilera et al. 2013a, b). Recently, the EU Common Agricultural Policy Reform 2014–2020 has provided a set of policy instruments to promote climate change mitigation and adaptation actions among farmers.

Environmental policies at the EU level can effectively mitigate polluting emissions. For example, the Nitrate Directive is having low but positive effects on the reduction of the emission of N compounds to the environment (6 % reduction for N_2O; Velthof et al. 2014). Furthermore, the development of other non-climate policies focused on the prevention of environmental problems such as soil fertility depletion and erosion as well as loss of biodiversity has also enhanced GHG reductions from the primary sector (Smith et al. 2007). Therefore, when aiming an effective reduction of GHG emissions globally, holistic schemes linking appropriate policies dealing with food, agriculture, waste, health, climate change, biodiversity and energy would be advantageous.

Halsnæs et al. (2012) have studied the convenience of the application of a mix of policies including energy and climate change mitigation options at the same time. Such a mix of policies should also recommend diet changes (e.g., the Mediterranean diet or the demitarian diet; see The Barsac Declaration 2010) as an efficient way to effectively mitigate climate change, to improve the quality of the environmental and the health of the Spanish population and to reduce the large external dependency on food and feed.

5 Conclusions

This paper has shown that in Spain a complementary approach focused on consumption-based emissions is paramount to achieve true mitigation of the nation's GHG emissions. The contribution of the Spanish agricultural sector to N_2O emissions has doubled during the last 50 years due to an intensification of agriculture. On average, 1.5 % of the new reactive N entering the environment yearly in Spain is emitted as N_2O due to agricultural activities. Emissions from imports, mainly cereals, soybeans and soy cakes, have increased faster than the emissions of the commodities produced in the country for export (e.g., citrus, vegetables, olive oil, wine and pig meat). As a result, consumption-based emissions are today 45 % higher than the emissions derived from agricultural production. Most of the N_2O emissions net imported to Spain in 2009 originated in non-Annex I countries of the Kyoto Protocol, leading to emission leakage in the Spanish agricultural sector. The most important driver of the observed changes is a significant increase in both feed production and import that mainly responds to the increasing demand for animal protein by the Spanish population. We advocate policies that could integrate both mitigation practices in the agricultural sector and actions on consumption, particularly those aiming at reducing animal protein in the human diet.

Acknowledgments This paper is the result of an international collaboration among several research institutions presented in the 2nd Workshop of the REMEDIA network, held in Zaragoza in April 2013. We wish to thank the FIRE (Fédération Ile de France de Recherche en Environnement, CNRS and UPMC) and the Research in Paris Programme (Paris City), which have supported the research of Luis Lassaletta in France. Guillermo Pardo would like to thank the Spanish National R+D+i Plan (CGL2009-10176, AGL2012-37815-C05-04) for financial support. The views expressed in this document are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission. We thank Javier Castrillo who developed several computer routines for the data management. We sincerely acknowledge the anonymous referees and the editor for their thorough and constructive revision on the manuscript.

Appendix: Technical notes about the emission factors

The N_2O EFs for most of the studied crop products were calculated as averages of the values provided in the LCA databases USDA, LCA Food DK and Ecoinvent (USDA 1998; Nielsen et al. 2003; Ecoinvent Centre 2007,), implemented in SimaPro 7. These

Table 3 Weight of primary matter per kg of processed product and proportion of the N_2O emissions allocated to the co-products

Product	Category	kg Primary Matter/kg product	Allocation
Sugar, Non-Centrifugal	Sugar & Sweeteners	7.47	0.87
Sugar (Raw Equivalent)	Sugar & Sweeteners	7.47	0.87
Sweeteners, Other	Sugar & Sweeteners	7.47	0.87
Honey	Sugar & Sweeteners	0.00	0.00
Soybean Oil	Vegetable Oils	5.40	0.38
Groundnut Oil	Vegetable Oils	5.00	0.70
Sunflowerseed Oil	Vegetable Oils	2.50	0.85
Rape and Mustard Oil	Vegetable Oils	2.33	0.74
Cottonseed Oil	Vegetable Oils	3.13	0.70
Palmkernel Oil	Vegetable Oils	2.00	0.17
Palm Oil	Vegetable Oils	4.64	0.81
Coconut Oil	Vegetable Oils	6.25	0.70
Sesameseed Oil	Vegetable Oils	5.00	0.70
Olive Oil	Vegetable Oils	5.00	1.00
Ricebran Oil	Vegetable Oils	10.00	0.10
Maize Germ Oil	Vegetable Oils	10.00	0.10
Oilcrops Oil, Other	Vegetable Oils	5.00	0.70
Wine	Beverages	1.50	1.00
Beer	Beverages	0.24	1.00
Beverages, Fermented	Beverages	3.25	1.00
Beverages, Alcoholic	Beverages	3.25	1.00
Alcohol, Non-Food	Beverages	3.25	1.00
Cake of Copra	Cakes	12.50	0.30
Cake of Cottonseed	Cakes	1.89	0.30
Cake of Groundnuts	Cakes	2.00	0.30
Cake of Linseed	Cakes	2.00	0.30
Cake of Maize	Cakes	3.33	0.30
Cake of Oilseeds, Nes	Cakes	2.00	0.30
Cake of Palm Kernel	Cakes	2.00	0.02
Sunflowerseed cake	Cakes	2.33	0.15
Cake of Rapeseed	Cakes	1.82	0.26
Cake of Soybeans	Cakes	1.29	0.62
Cake sesame	Cakes	2.00	0.30

Table 4 Emission factors used for the animal production

Product	EF (g $N\text{-}N_2O$/kg product) for products produced in Spain	EF (g $N\text{-}N_2O$/kg product) for imported products	EF (g $N\text{-}N_2O$/kg product) for exported products
Bovine Meat	7.45	10.80	16.56
Sheep *(Ovis aries)* & Goat Meat (*Capra aegagrus*)	3.27	10.99	9.11
Pigmeat	1.00	2.49	2.70
Poultry Meat (*Gallus gallus*)	0.49	1.86	2.14
Meat, Other	0.49	1.86	2.14
Butter, Ghee	n.a.	3.39	3.26
Cream	n.a.	0.92	0.89
Eggs	0.49	1.70	1.56
Milk	0.12	0.53	0.51

Source: Schenck 2006; Cederberg et al. 2009; Vergé et al. 2009; Da Silva et al. 2010; Leip et al. 2010

products are wheat, rice (*Oryza sativa*), barley, maize, rye (*Secale cereale*), oats (*Avena sativa*), sorghum (*Sorghum* sp.), other cereals, potatoes, sugar cane (*Saccharum officinarum*), sugar beets (*Beta vulgaris*), pulses, sunflower (*Helianthus annuus*) seed, rape (*Brassica napus*) and mustard (*Sinapis* sp.) seed, cotton (*Gossypium* sp.) seed, other oil crops, tomatoes (*Solanum lycopersicum*), other vegetables and other fruits. World median EF values from Nemecek et al. (2011) were used for treenuts, groundnuts (*Arachis hypogaea*), palm kernels (*Elaeis guineensis*), onions (*Allium cepa*), oranges (*Citrus* x *sinensis*) and mandarins *(Citrus reticulate*), bananas and platains (*Musa* x *paradisiaca*) and apples (*Malus domestica*). Data from Audsley et al. (2009) was used for estimating the EFs of tea (*Camelia sinensis*), pepper (*Piper nigrum*), pimento (*Capsicum annuum*), cloves (*Syzigium aromaticum*) and other spices. Coffee (*Coffea* sp.) EF was taken from Hergoualc'h et al. (2007). When we did not find specific EFs, we used the EF of a similar crop. Particularly, sorghum EF was used for millet (*Panicum miliaceum*); potato EF for cassava (*Manihot sculenta*), sweet potatoes (*Ipomoea batatas*) and other roots; pulses average EF for beans and other pulses; oilcrops average EF for coconuts (*Cocos nucifera*) (incl. copra); sunflower and rapeseed average EF for sesame (*Sesamum indicum*) seed; oranges EF for lemons (*Citrus x limon*), limes (*Citrus x aurantifolia*), grapefruit (*Citrus x paradise*) and other citrus; coffee EF for cocoa (*Theobroma cacao*) beans; and banana EF for pineapples (*Ananas comosus*) and dates (*Phoenix dactylifera*).

Table 5 Production and trade of bovine meat in 2009 in Spain

	1000 Tonnes
Production	5313
Import Quantity	540
Export Quantity	1420
Imported as live animal	183
Exported as live animal	23

Table 6 Emission factors for cattle

EF	g N-N_2O/kg product
For cattle meat produced in Spain	7.45
For imported cattle meat	10.80
For exported cattle meat	16.56

Given the uncertainty in LCA-based EFs of soybeans, and the importance of this crop in Spanish international trade, an empirically-based EF of 1.253 g N-N_2O/kg product was calculated using world average emission data from Jensen et al. (2012) and yield data from FAOStat. The EFs of grapes, olives and forages were 0.058, 0.189 and 0.201 g N-N_2O/kg product, respectively, and they were estimated using Spanish data, as described in the methods section.

The EFs of the processed products were calculated from EFs of primary products using processing ratios obtained from Ecoinvent (Ecoinvent Centre 2007), FAOSTAT, and from own estimations (Table 3). Economic allocation was used to divide the N_2O emissions between the co-products. All meat values refer to carcass weight. Poultry meat EF was assumed for other meat. Butter and cream were assumed to have 80 % and 18 % fat contents, respectively. Allocation of emissions from the incoming milk to dairy products was done using dry mass as a suitable proxy for economic value. Milk category refers to raw milk assuming 4 % fat content (Table 4).

Herein we present an example of the calculation of N_2O emissions associated with animal products. As we indicate in the methodology section, the calculation of N_2O emissions associated with animal products requires particular attention. We considered different EFs for production, imports and exports, in order to reflect differences between Spanish and foreign production systems, and to avoid double counting of emissions involved in other sections of the study. All these calculations require a last correction for meat because production data include not only national production (indigenous meat), but also those animals imported alive that are slaughtered in Spain. Herein we present the example of the calculations for bovine meat N_2O emissions (Tables 5, 6, 7 and 8).

For products produced in Spain we only took into account N_2O emissions associated with manure management and direct excretion of grazing animals because other emissions have been already accounted in the crops and processed products calculations. For imported products we used a complete EF that includes also feed production. This EF is general and not specific to any country. For exported cattle meat we used a complete EF (i.e., including feed production) specific for Spain. For imported as live animals we used same EF as for imported cattle meat. For exported as live animals only feed production is considered (9.13 g

Table 7 Results of the production multiplied by the EF

N_2O Emissions	Gg N-N_20
Production	4.46
Import	1.87
Export Quantity	1.94
Imported as live animal	1.98
Exported as live animal	0.21

Table 8 Emission of N-N_2O associated to production, import and export of cattle meat in 2009

	Gg N-N_20
Production	2.48
Import Quantity	3.84
Export Quantity	2.15

N-N_2O/kg product; Leip et al. 2010). Finally, we correct the emission taking into account the live animals: To the final account we remove imported as live animals to the production and we add this to the import value. We also add exported as live animals emissions to the export emissions.

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